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Elimination of Emitter-Mesa Etching and Complete Planarization of Heterojunction Bipolar Transistors via Doping Selective Base Contact and Selective Hole Epitaxy

T.Y. Kuo [*], K.W. Goossen, J.E. Cunningham, C.G. Fonstad [*],F.Ren,and W. Jan

AT&T Bell Laboratories, 4B-527, Holmdel, NJ 07733 (201)949-6979

[*] Massachusetts Institute of Technology, Cambridge, Mass. 02139

We achieve for the first time a heterostructure bipolar transistor (HBT) with a base δ-doping of $6 \times 10^{14} cm^{-2}$, near the physical limit of one monolayer (ML). The devices show a current gain of 15. The doping confinement of the δ layer is 15Å. To fabricate the HBT without inducing dopant diffusion or using critical etching, we have developed a new low-temperature base-contacting procedure ($T_{\max} = 420C.$) which requires no base-emitter etching. In addition, this technique greatly reduces surface recombination and yields a planar structure. We also have investigated complete planarization of HBT's as well as other molecular beam epitaxy (MBE) grown devices by performing the growth in holes.

We have developed a techniques for contacting the base in a heterojunction bipolar transistor (HBT) without base-emitter etching and without high temperatures ($T_{\max} = 420C.$). The elimination of exposed emitter mesa sidewalls greatly reduces surface recombination. Using this technique, we have produced HBT's with a gain of 200. This technique is especially applicable to HBT's with thin bases (~100 Å) and extremely high dopant concentrations since there is no sensitive etching and no high temperatures which would cause dopant diffusion. We have explored the limit of thin-base doping by producing HBT's which have δ-doped bases of concentration $6 \times 10^{14} cm^{-2}$ (1/2 monolayer coverage). TEM studies reveal that the δ-layer is confined to about 15Å.[1] Our δ-HBT has a gain of 15 with a base resistance of 100 Ω/square. Another advantage of emitter-mesa elimination is partial planarization of the structure. We also have investigated complete planarization of HBT's as well as other molecular beam epitaxy (MBE) grown devices by performing the growth in holes.

Previous techniques for contacting the base without etching have required ion implantation[2] which causes crystal damage and needs a high-temperature (~800 $C.$) annealing step. We have developed here a simple technique for contacting the base without exposing the base to air that requires only a low temperature anneal (420 C.). We evaporate Au-Zn (or Au-Be) and alloy at 420 C. for 10 sec., forming a p^+ region under this contact and forming an ohmic contact to the p-type base and a rectifying contact to the emitter (Fig. 1). Hence the term "doping selective contact". We use a non-alloyed in situ grown aluminum emitter contact which allows the emitter to be thin, so that the Zn can easily diffuse to the base.

Our HBT structure (conventional base) consists of a GaAs n^+ subcollector and n^- collector which are

0.3 μm and 0.5 μm thick respectively on an n^+ substrate. The 0.1 μm p^+ GaAs base is doped with Be at a concentration of $3 \times 10^{18} cm^{-3}$. The $n^-(10^{17} cm^{-3})$ 0.1 μm $Al_xGa_{1-x}As$ emitter is graded from x=0.3 at the base to x=0. This is followed by several n^+ delta-doped Si layers and 0.1 μm of aluminum deposited in the MBE chamber which forms an ohmic contact with the emitter.[3] To fabricate devices, the aluminum is etched to form 50 μm diameter circular contacts. A Au-Zn annulus was deposited around the emitter for the base contact. Circular mesas encompassing this are then etched to the substrate for collector mesa definition. An excellent base-emitter diode characteristic was obtained for the conventional HBT, with forward and reverse breakdown voltages of 0.8 and -7 volts respectively. The leakage current was less than 5 μA. The maximum incremental gain of the HBT was 200, and was greater than 175 for collector currents from 8 mA to 50 mA. This uniform current gain could be the result of reducing base-emitter surface recombination. In addition, the collector current saturation characteristics are flat which indicates a very small modulation of the base (Fig 2). A slight negative resistance at high current observed is due to the thermal heating effect. V_{CEO} was 8 volts.

The δ-HBT structure is similar to above except that the base is a 200Å undoped layer with a δ-Be sheet of a real concentration $6 \times 10^{14} cm^{-2}$. TEM studies revealed that the Be δ-doped layers are confined to 15Å, which is exceptional since this concentration of $5 \times 10^{21} cm^{-3}$ greatly exceeds typical solubility limits of $1 \times 10^{19} cm^{-3}$ in GaAs.[1] Hall measurements show δ-Be to have complete electrical activity with room temperature hole mobilities of $50 cm^2/V{-}sec$, 10 times higher than predicted by theoretical models at this concentration. The base sheet resistance is less than 100 Ω/square. The emitter-base junction has an ideality factor of 1.4 and reverse diode breakdown of 7 volts. The leakage current is less than 5 μA. This excellent b-e junction, as well as SIMS profiles of the sample, indicate the absence of significant Be diffusion into the emitter. The transistor has a dc current gain of 15 (Fig. 3). V_{CEO} is typically 8 volts.

It is advantageous to have completely planar devices so that subsequent fine-line contact lithography in the regions outside the device may be performed. We therefore investigated complete device planarization by growing our devices selectively in pre-etch holes. We made holes 1.2 μm deep and then grew and fabricated an HBT as outlined above. The base emitter diode had turn on and reverse breakdown voltages of 1.2 volt and -5 volts. The maximum current gain achieved was 100. The V_{CEO} is typically 7 volts. The lower current gain of this device may be caused by leakage current along the side of the growth. In order to more carefully evaluate the quality of the material grown in the holes, and to investigate the sidewall leakage phenomena, we have grown and fabricated $p{-}i{-}n$ quantum well light modulators in the holes. With these devices we may investigate reverse bias leakage and also the quality of quantum well growth in the hole by performing photocurrent spectroscopy. The as grown sample had soft breakdown (about 50μA at 3 volts reverse bias). Then we etched an inner mesa inside the hole, and the leakage current vanished. The resulting hard breakdown voltage of the diode was between 25-30 volts typically. This confirms that the leakage was along the growth sidewall. In addition we observe sharp quantum well exciton features in photocurrent spectra of our sample which indicates that the material grown in the hole is excellent.

Eliminating the need for an emitter mesa is of great importance to HBT technology since it makes possible to fabricate thin base and high density δ-HBT. It also reduces base-emitter surface recombination, removes a sensitive etch process in the fabrication, and makes the structure more planar. We also grew and fabricated completely planarized HBT's and quantum well light modulators in holes. Such planarization allows subsequent fine-line contact lithography in the regions outside the device.

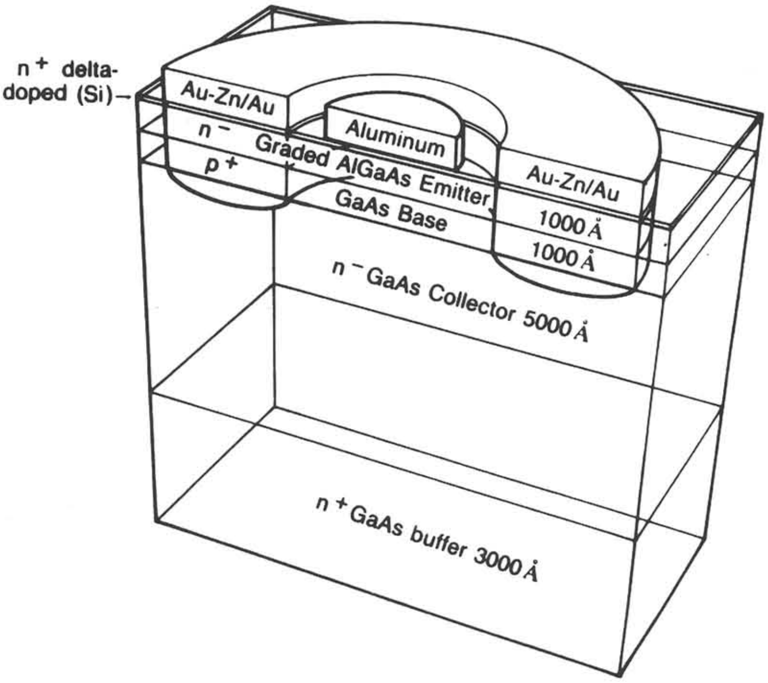

Fig. 1: Doping-selective base contact HBT structure.

References

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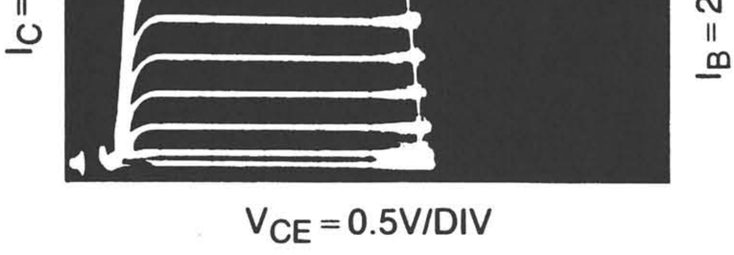

Fig. 2: Doping-selective base contact HBT I-V's showing current gain of 200.

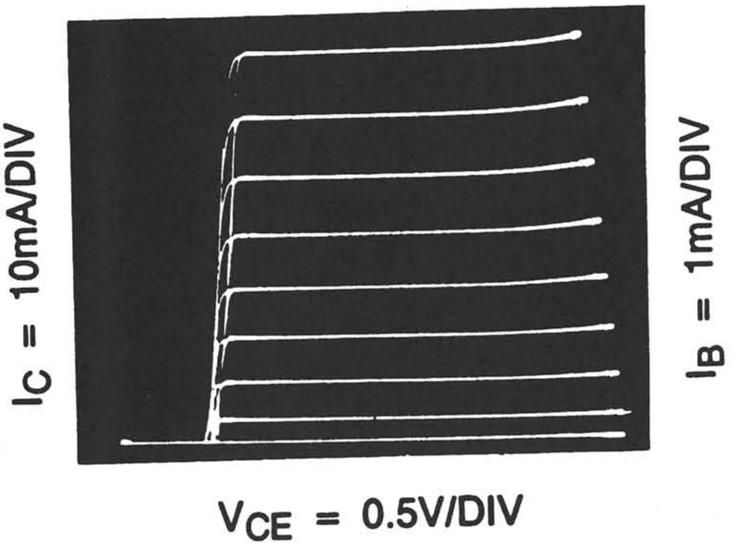

Fig. 3: δ-doped base HBT I-V's showing gain of 15.